A DIURNAL VARIATION OF THE INTENSITY AND ENERGY SPECTRUM OF LOW ENERGY ELECTRONS INCIDENT AT FT. CHURCHILL, CANADA+

by

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ABSTRACT

We report measurements of the intensity and energy spectrum of electrons incident at Ft. Churchill, Canada which confirm and extend the observations of a large diurnal intensity variation reported by Jokipii, L'Heureux and Meyer (1967). From our observations we conclude: (1) the effective daytime cut-off near Ft. Churchill is $\sim$ 160MV, (2) the night-time cut-off is $\sim$ 15MV but may fluctuate with time, and (3) the transition from day to night conditions occurs within a period of one hour between 1800 and 1900 hours local time. These results are related to the predictions of recent calculations based on the entrance of particles through the magnetospheric tail and their subsequent motion in the geomagnetic cavity. The re-entrant albedo intensity between 16-160 MeV present in the daytime is compared with other observations of these particles at lower latitudes. The extra-terrestrial electron intensity present at night between 15 and 160 MeV is obtained and found to be substantially lower than previous observations have indicated.

INTRODUCTION

Recently, Jokipii, L'Heureux and Meyer (1967) (JHM) have observed a diurnal variation of low energy electrons at Ft. Churchill in Canada. They find that the intensity of electrons between 10 and 220 MeV is roughly twice as large in the daytime as at night. As a result of the fact that the intensity of re-entrant albedo electrons is larger than the intensity of extra-terrestrial electrons in this energy range a reduced geomagnetic cut-off at night would actually result in a reduced intensity of electrons at night. Following this interpretation the above authors explain their electron variations in terms of a lowered geomagnetic cut-off during the night. In the course of observations of this variation the increase in intensity is always observed at approximately 0600 hours local time. The authors lament the fact that none of their flights were aloft at the time when the corresponding decrease in intensity would be expected around 1800 hours local time.

We would like to report measurements of electrons made in the summer of 1966, also at Ft. Churchill, which clearly show this decrease in intensity at 1800 hours local time. The features of this decrease are compared with those of the increases observed by JHM and the symmetry of the diurnal cut-off change responsible for these electron changes is examined. The energy resolution of our instrument permits a detailed examination to be made of the cut-off changes, and values obtained for the quiet daytime and night-time cut-offs at Ft. Churchill. These cut-offs are compared with theoretical predictions.

THE OBSERVATIONS

The detector system used in these studies was a scintillation counter telescope containing within its geometry a gas Cerenkov detector operated as a threshold device, a lead glass Cerenkov total energy spectrometer, and following this element, a third scintillation counter to sample shower development at a depth of 7.5 radiation lengths. The gas Cerenkov detector contained Freon gas at one atmosphere and was used to select particles whose energies were at least $30m_oc^2$. The response of this instrument to electrons has been discussed by Webber and Chotkowski (1967a) and the results of the 1965 and 1966 flights have also been presented. (Webber and Chotkowski (1967b), Beedle and Webber, (1967)). For the purposes of this paper it is sufficient to note that the energy of the electrons is determined solely by the pulse height in the lead glass total energy spectrometer. A high resolution print out of the smaller pulse sizes in the lead glass spectrometer enables the electron energy spectrum from

15-250 MeV to be obtained in 5 MeV increments. The material in front of the lead glass spectrometer is minimized to prevent scattering and totals ~ $2.5^{g}/cm^{2}$ - mostly plastic. Between the energy limit of 5 MeV imposed by this material and the 15 MeV limit imposed by the gas Cerenkov detector the electron spectrum can also be obtained, albeit with somewhat less accuracy.

The manner in which the electron spectrum below 220 MeV is obtained in this experiment and the one of JHM differ sharply. In the later experiment only one low energy interval, from 10 to 220 MeV, is available and is obtained by what is effectively a range measurement. As a result of our energy resolution we can examine the spectral changes taking place at low energies in considerably more detail. Further, there appears to be a systematic difference in the intensities of low energy particles measured by the two techniques, with the range measurement giving intensities about 1.5x higher than our instrument. It should be noted, however, that this difference does not significantly alter the respective comparisons and conclusions regarding the observed diurnal variation.

The results discussed in this paper are based on a balloon flight made at Ft. Churchill, Canada on July 25, 1966. The equipment reached altitude at 1400 hours local time (LT) and floated essentially level at 2.5mb until

2300 hours LT when sunset caused the balloon to descend slowly. The flight was terminated at sunrise the next day. According to the tabulations of Shea and Smart (1966) the internal field cut-off at Ft. Churchill is 210MV ($L = 8.72$; $\lambda eff = 69.7^{o}$). During the course of the flight, however, the balloon drifted 500 miles to the west, during which time the cut-off changed systematically from 230MV to 280MV. The effective cut-off for the daylight portion of the flight is therefore 250 $\pm$ 20MV, the difference between this value and the one relating to Ft. Churchill itself, being significant in the analysis that will take place.

Intensity versus altitude and time data for electrons in the energy range 15-160 MeV is shown in Figure 1. T = O corresponds to 1400 hours LT. It is seen from the figure that at approximately 1800 hours LT the intensity of these electrons decreased by a factor of two, remaining at this lower level for the duration of the flight. The estimated intensity of secondary electrons as a function of altitude and time is shown by the lower solid curve. A similar intensity versus altitude and time curve for electrons from a flight one month earlier as reported by JHM is also shown. These later intensities have been divided by two to normalize with our data. Some of this intensity difference arises because of the larger energy interval used by the above authors, but there remains a systematic difference ≈ 50% observable at all altitudes and times as noted earlier. The intensity-altitude curves from the two experiments are virtually identical and more importantly the fractional contributions of atmospheric secondaries in both instances is practically the same. This assures that even though the intensity of atmospheric secondaries at peak altitude is ≈ 50% of the total intensity of all electrons during the night, any differences in the interpretation of the diurnal effects cannot be due to differing corrections for these atmospheric secondaries. We might also add that this agreement provides additional support for the magnitude of the respective corrections for secondary electrons that must be made in order to obtain the flux of electrons incident on the top of the atmosphere. In the case of the Chicago flights the balloons all reached altitude at night so that the 0600 hours local time increase in intensity was observed. The 1800 hour transition practically mirrors the morning one - even the day and night fluxes and flux ratios as measured in the two experiments are the same. On the basis of our measurement it does appear that the 1800 hour transition is more abrupt than the one at 0600 hours.

The intensity-time behaviour of electrons in various energy ranges is displayed in Figures 2 and 3. In addition to the relatively constant intensity of 160-320 MeV electrons exhibited in Figure 2 we can also state that no significant variations were noted in any of the still higher energy intervals.

With regard to the data presented in Figure 3 we see that no comparable variation occurs in the total cosmic ray intensity, which is, of course, predominantly protons with rigidities well above those associated with the electron changes. This observation along with that relating to the constancy of the higher energy electrons, and careful pre and post flight checks eliminate any possibility that the observed changes could be instrumental.

Of particular interest is the behaviour of the 5-15 MeV electrons. The intensity variations of these particles are clearly outside of the experimental uncertanties, although the large decrease associated with the 15-160 electrons is not in evidence. This suggests to us that the lower energy limit for electrons participating in the changes may be fluctuating at about 15 MeV.

The situation is summarized in Figure 4 where we show the differential spectra of all electrons measured separately for daytime (1400-1900 hours local time) and night-time (1900-2400 hours local time), Other related observations are also shown including those of JHM. The changing flux of electrons is rather clearly isolated to the energy range 15-160 MeV. We note in passing that our total electron intensities at low energies agree closely with the results at nearly the same altitude reported by Freier and Waddington (1965) and by Schmoker and Earl (1964), when one considers the time of day at which these earlier measurements were made. In these experiments the electrons can be identified unambiguously, although unfortunately the statistical accuracy of the results leaves something to be desired.

INTERPRETATION OF DIURNAL VARIATION

It should be clear from the foregoing presentation that our results substantiate, and because of our energy resolution extend, the interpretation for the diurnal variation of low energy electrons given by JHM. This interpretation is based on the day-night assymetry of the geomagnetic field cavity and the effect of this assymetry on the local cut-off rigidity at a high latitude station. The following situation is assumed to exist at Ft. Churchill. During the day, for particles below a certain rigidity, R_D, the lines of force effectively "connect" to the opposite hemisphere and as a result we expect a flux of return albedo electrons at Ft. Churchill. Above this rigidity there is no such connection and particles can arrive directly from interplanetary space so we are presumably sampling the full intensity of extra-terrestrial electrons. At night the maximum rigidity R_N for which lines of force connect to the opposite hemisphere is greatly reduced and conversely we are sampling the full intensity of extra-terrestrial electrons down to this rigidity.

In this picture the large flux of electrons < 200 MeV observed during the day contains re-entrant albedo particles. At night these particles are absent (above 15 MeV) and are replaced by true extra-terrestrial electrons. This requires one to believe that the flux of re-entrant albedo electrons is larger than the flux of extra-terrestrial ones in this energy range (by a factor ~ 2 at the lowest energies). The results quoted by JHM (1967) substantiate this contention as do our own results. If this picture is correct then we might, at first glance, expect to see a "kink" in the daytime spectrum of electrons occurring at a rigidity ~ R_D and representing a transition from a larger flux of low energy re-entrant albedo to a smaller flux of higher energy extra-terrestrial electrons. Because of the fact that this cut-off is probably not sharp, and also because the difference in the magnitudes of the two spectra is most likely only a factor ~ 1.5 at this energy, the effects of this transition might not be readily evident. A completely biased look at the daytime spectrum in Figure 4 shows a possible kink occurring at ~ 160MV.

The previous arguments indicate that measurements of the diurnal variation of low energy electrons at Ft. Churchill may be used to study cut-off variations there and so to relate to theoretical models of particle motion in the assymetric magnetosphere. In this connection the relevant features of our measurements are:

(1) An effective daytime cut-off of ~ 160MV.

(2) A night-time cut-off of about 15MV which may fluctuate with time. Below this rigidity the full re-entrant albedo intensity is still presumably incident on the top of the atmosphere.

(3) A transition from day to night conditions occurring within a period ~ 30 minutes between 1800 and 1900 hours LT.

RELATION OF OBSERVATIONS TO THEORETICAL PREDICTIONS

At any point on the earth's surface one can define a cut-off rigidity for cosmic rays arriving at a particular zenith and azimuth using a suitable modification of Stormer's theory for the motion of charged particles in a dipole field. Discrepancies between the measured cosmic ray cut-offs and those expected from a representation of the earth's internal magnetic field have been clearly demonstrated. A review of the situation may be found in the paper by Reid and Sauer (1967). It suffices to say that the actual cut-off at high latitudes and particularly around the polar cap is still uncertain, and the experimental measurements are very limited. The magnetic field configuration which is responsible for the very low energy cut-off is complicated and is strongly influenced by the solar wind which deforms the magnetosphere and creates the magnetospheric tail. The importance of this tail on cosmic ray cut-offs has been recognised only recently (Michel, 1967, Reid and Sauer, 1967). The particular day-night assymetries in the effective cut-off introduced by this tail have been discussed by Gall et. al.,(1967) and by Taylor,(1967). To assist in our discussion we present, in Figure 5, a schematic diagram of the geomagnetic field configuration as adapted from the work of Taylor (1967). With this field configuration in mind we may divide the surface of the earth into magnetic latitude zones which have the following characteristics during geomagnetically quiet times.

1. A zone, at latitudes $\lesssim 60^{o}$, in which the field lines, although distorted by current systems and solar wind pressure, always connect to conjugate points in the opposite hemisphere. This zone corresponds roughly to the region of trapped radiation, and to a region where the cosmic ray cut-offs are described by the earth's internal

field plus the possible addition of ring currents flowing in the magnetosphere. (Akasofu et. al. (1963)). In this region also the day-night changes in cut-offs would be expected to be small.

2. A polar zone, in which the emerging geomagnetic lines of force exhibit a behaviour that is strongly dependent on the local time of day. During daylight hours the field lines are seen to connect up to latitudes $\approx 81^{\circ}$. At still higher latitudes and at all latitudes $> 60^{\circ}$ during the night the field lines are drawn back into the geomagnetic tail.

At the location of Ft. Churchill, ($\lambda \approx 70^{\circ}$) then we might expect a very large diurnal variation in cut-offs. At local noon the cut-off might be expected to be an extension of that experienced at lower latitudes while at midnight the method of arrival of particles is totally different and a cut-off dependent on properties of the magnetospheric tail will be more in order.

Before discussing the theoretical predictions for Ft. Churchill and comparing them with our own work we should briefly discuss the observations of Stone (1964) which bear directly on this problem. In a satellite experiment he finds the local time dependence for the cut-off of 1.5 MeV protons (50MV). According to the definition adapted by Stone this cut-off was 67° on the dayside and 65° on the night side as compared with a theoretical Stormer cut-off of 76°. These latitudes characterize the locations at which an excess flux of low energy solar particles incident over the polar regions is first observable. The latitudes at which the maximum (plateau) flux is first observed are $\approx 71^{\circ}$ and 66° respectively; the daytime value being quite variable and ranging from 74° to 68°.

The manner in which a cut-off rigidity is defined under such circumstances of a non-sharp cut-off (particularly in the daytime) is presently one of individual preference. For purposes of comparison with our results we suggest that the value of 71° for the daytime cut-off of 1.5 MeV protons, from the work of Stone, is most appropriate.

In Figure 6 we show our measured values for the daytime and night-time cut-offs as deduced from the electron measurements (plotted not at the effective latitude of Ft. Churchill of 69.6°, but at a latitude of 68.1° corresponding to a cut-off of 250MV, as noted earlier). The various solid circles are from balloon and satellite measurements (Sawyer. et. al., (1967)). The values from Stone's work are shown as squares, and the diamond is frpm the work of Akasofu et. al., (1963). If one allows for a variability in the daytime cut-offs as shown by the shaded area in the figure, it appears that the typical quiet-time cut-offs as a function of latitude can be reconciled with a single dashed curve as shown in the Figure. The cut-offs at night are much lower although the measurements are not yet sufficient to define a typical curve of night time cut-offs versus geomagnetic latitude.

A much more sensitive way of exhibiting the deviations of the cut-offs from those expected from the earth's internal field is to compare the fractional reduction in cut-off as a function of geomagnetic latitude. This is done in Figure 7 for the daytime cut-offs only. The explanation of a similar curve for latitudes $<60^{o}$ has been given in an earlier paper (Sawyer et. al. (1967)), and will not be repeated here. Our attention will now be directed to the theoretical picture regarding the cut-offs at high latitudes.

As has been noted, the work of Sauer and Reid (1967) is the first to deal specifically with the diurnal changes in cut-offs arising from the influence of the magnetospheric tail. Their results are not quantitative enough to compare with our measurements, however, except to note that the daytime cut-off is indeed expected to be considerably higher than the night-time one. According to the model for the geomagnetic field taken by them the night-time cut-off is expected to be essentially zero above a latitude of 65.9^{o}. The latitude at which the zero cut-off occurs depends on the minimum distance to which the current sheet associated with the geomagnetic tail penetrates which in this instance is $\sim 12\ R_e$.

Gall et. al., (1967), using the Williams and Mead (1965) model of the geomagnetic field, which includes the geomagnetic tail, have integrated ~150 orbits of low energy particles to find the characteristics of the cut-off. They find that, at noon, particles need not arrive through the compressed daytime field, but that they can penetrate through the tail, move around the earth and reach a particular location. As a result the increase in cut-off expected from the field compression on the daytime side, will be inhibited. These authors do not specifically determine the daytime cut-offs, however.

The night-time cut-offs are examined at one station, Kiruna (with an internal field cut-off ≈ 540MV) for various field strengths in the geomagnetic tail. For a tail field strength ≈ 40γ, the effective cut-off is ≈ 85MV - rising to ≈ 190MV for a tail field of 30γ. These calculated points are shown on Figure 6. It is obvious that the calculated cut-off for a tail field strength between 30 and 40γ is consistent with the night-time curve obtained from our measurements and those of Stone (1964).

Taylor (1967) has reversed the approach of Gall et. al. and has integrated orbits of particles of one particular energy, 1.2 MeV incident at many locations in the polar regions of the earth. His values for the daytime and night-time cut-off latitudes for these 1.2 MeV particles, incident vertically, are 76° and 65° respectively (Figure 6). Again the calculated night-time value is consistent with observations. Regarding the agreement between theory and measurement for the daytime cut-offs we should emphasize that the calculations of both Gall et. al. and Taylor, as well as the measurements of Stone, clearly indicate that the cut-off is not sharp in the Stormer sense. The band of latitudes just below the daytime cut-off latitude of 76° for 1.2 MeV particles as indicated by Taylor represents a region of complex orbits where apparently incoming particles become trapped or quasi-trapped in a manner similar to the main cone in Stormer theory. The direct measurements probably reflect the degree of transparency of this region to particles of various energies in this band arriving from infinity.

Finally consider the transitions from daytime to night-time conditions occurring at approximately 0600 and 1800 hours local time. The work of Taylor indicates that the 0600 transition is more gradual taking ≈ 3 hours whereas the 1800 hour transition is completed in ≈ 1 hour. The transition we observe at ~ 1800 hours is very abrupt taking ~ 1 hour or less. A study of the curves presented by JHM indicates a more gradual transition at 0600 hours taking place over 2-3 hours.

THE EXTRA-TERRESTRIAL ELECTRON SPECTRUM AT LOW ENERGIES

If the above picture of the diurnal electron variation is correct the interplanetary electron flux cannot reasonably be greater than the night-time flux above $\approx$ 15 MeV observed at Ft. Churchill. This point has been discussed and emphasized by JHM. By the same token the re-entrant albedo flux cannot be greater than the daytime flux at energies $\lesssim$ 160 MeV. In both instances we use the word greater - since a considerable fraction of the electrons observed at balloon altitude must be atmospheric secondaries. From our measurements (see e.g. Beedle and Webber, (1967)) and those of L'Heureux (1967) we believe this secondary correction can be accurately and consistently made (e.g. see Figure 1). If this secondary correction is made to the daytime intensities we obtain the re-entrant albedo intensity between 15-160 MeV. This intensity is shown in Figure 8 along with measurements of other observers - including particularly the comprehensive study of Verma (1967) at higher energies. The agreement between the different measurements supports the contention that the particles observed at Ft. Churchill are re-entrant albedo, we believe, although again we note a difference of approximately 50% in our flux below 150 MeV and that measured by Verma using a range technique.

If the same subtraction of secondaries is performed on the night-time flux the resulting extra-terrestrial flux incident on the top of the atmosphere is obtained. This spectrum is shown between 15 and 160 MeV and combined with our observations at higher energies, to 6 BeV. The observations of L'Heureux (1967) at higher energies and of JHM in the 15-240 MeV are also shown. The systematic difference at low energies is again evident. The intensity of these extra-terrestrial electrons at low energies is considerably below the values quoted in the past (Meyer and Vogt,(1961); L'Heureux (1967)). In addition the spectrum appears to be almost flat between 20 MeV and 300 MeV.

The implications of these remarkable new features of the extra-terrestrial electron spectrum unveiled by the diurnal cut-off variation will be discussed in a subsequent paper.

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FIGURE CAPTIONS

Figure 1. Intensity of all electrons from 15-160 MeV as a function of altitude and time observed on July 25, 1966 at Ft. Churchill. (Solid circles and solid line). The lower solid line shows the contribution of atmospheric secondary electrons. The corresponding measurements of JHM (1967) in the energy range 10-240 MeV in June 1966 are shown as open squares and continuing dotted line. (All fluxes divided by 2). Their contribution of secondary electrons is shown as a dashed line.

Figure 2. Intensity versus time for electrons in the energy range 15-160 MeV and 160-320 MeV. The time is local time at Ft. Churchill. At the location of the balloon the local time at 1900 hours is approximately one hour earlier.

Figure 3. Intensity versus time for electrons in the energy range 5-15 MeV, and of the total cosmic ray flux.

Figure 4. The differential energy spectra of all electrons between 5 and 700 MeV observed at $2.3^{g}/cm^{2}$ at Ft. Churchill.

Daytime (1400-1900 LT) intensities are shown as open diamonds, night-time (2000-2400 LT) as solid diamonds. (1) Refers to the measurements of Meyer and Vogt (1961). (2) Refers to the day-night measurements of JHM (1967). (3) Is from Freier and Waddington (1965) (includes time both during the day and at night). (4) is by Schmoker and Earl (1965).

Figure 5. Field lines in the noon midnight meridian of the geomagnetic field. The axis are labelled in units of earth radii and the field lines are labelled by their colatitude at the surface of the earth. After Taylor (1967).

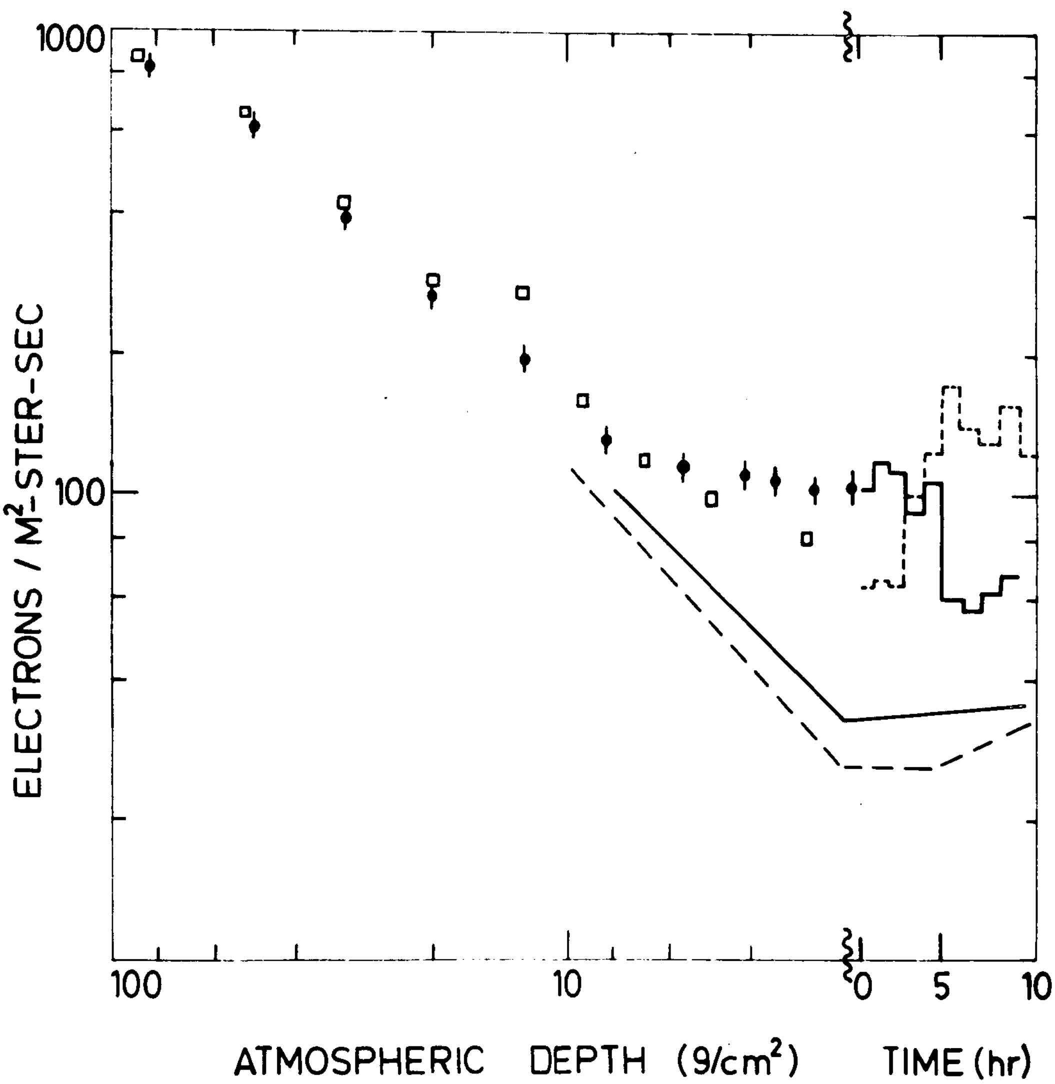
Figure 6. Some values for measured and calculated day and night cut-offs. Measured values are discussed in the text; ⊗ represents the calculation of Taylor (1967), x for Gall et. al. (1967). The latitudes are determined by $\lambda_{eff} = \cos^{-4}\left(\frac{P_c}{14.9}\right)$ where P_c is from the work of Shea and Smart (1966).

Figure 7. Same data as in Figure 6 except the fractional reduction of cut-off $\left(\frac{\Delta P}{P_c}\right)$ is plotted.

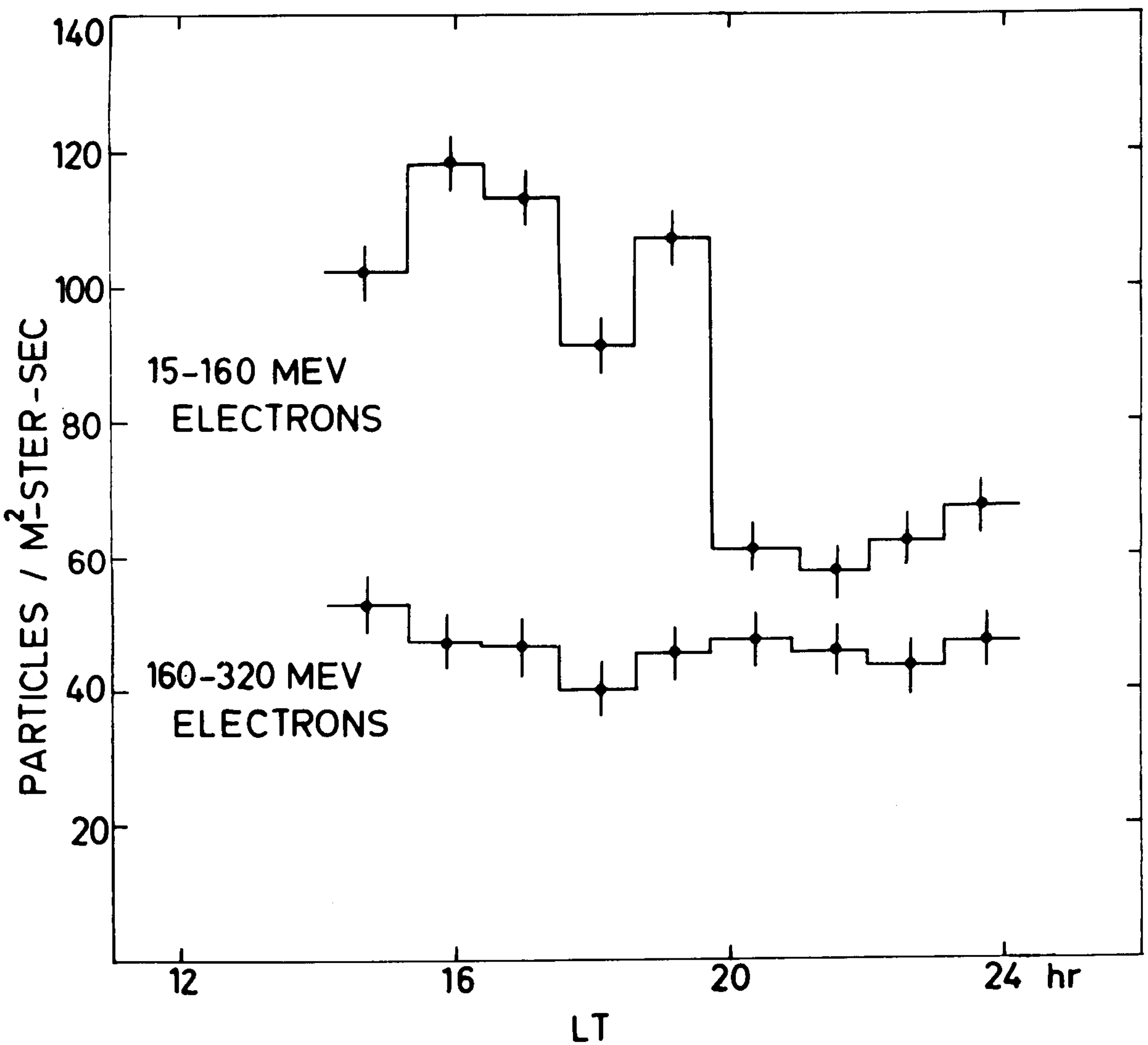
Figure 8. Various measurements of the spectrum of re-entrant albedo electrons. This measurement is shown as solid diamonds. Verma's (1967) work is shown as solid circles. The data from

Schmoker and Earl (1965) as open squares.

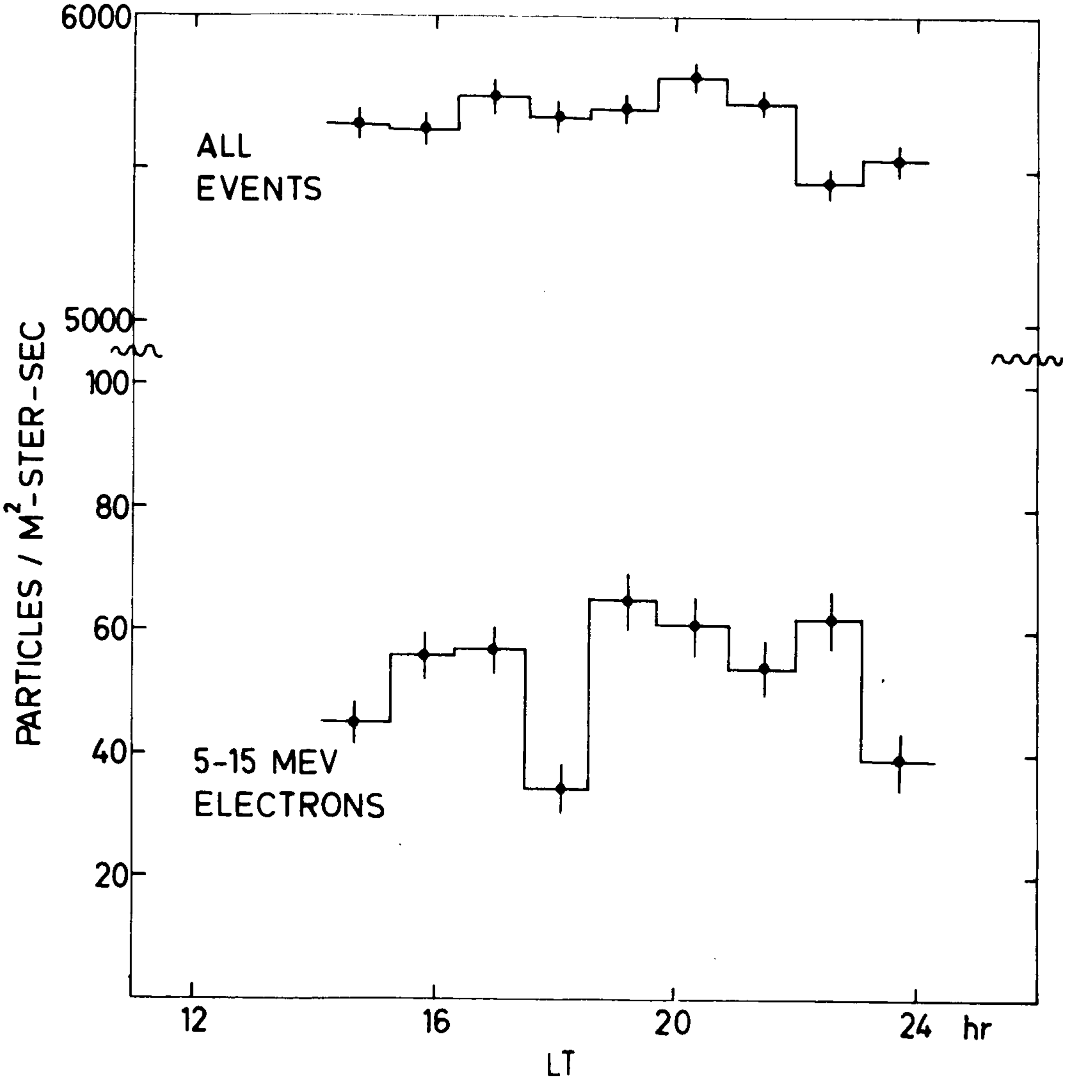
Figure 9. The extra-terrestrial electron spectrum in 1966. This measurement and that of Beedle and Webber (1967) are shown as diamonds. JHM as a bar between 15 and 240 MeV. L'Heureux (1967) as open circles; and Cline et. al (1964) as crosses.



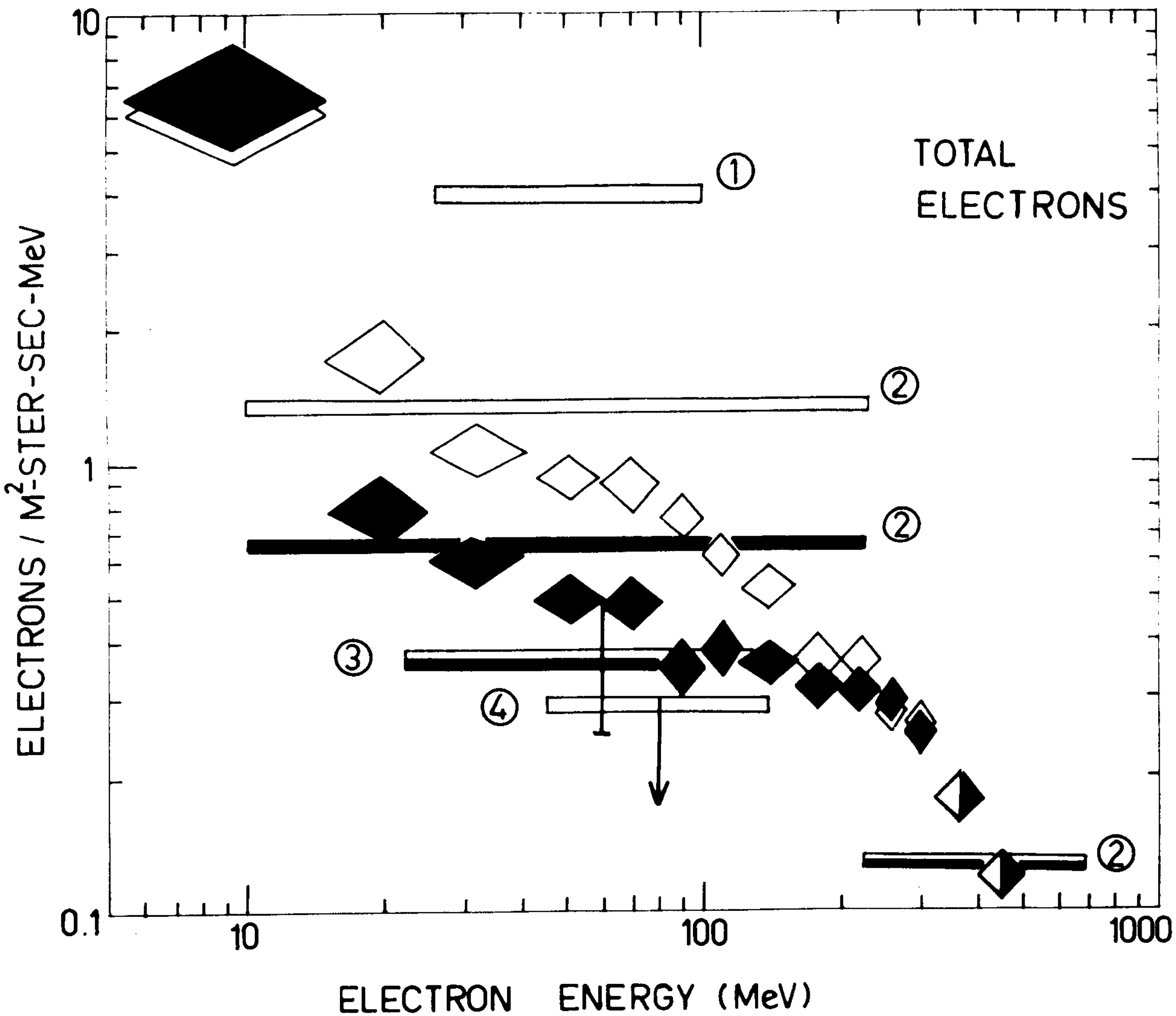
1000
100
ELECTRONS / M^2-STER-SEC
100
10
0
5
10
ATMOSPHERIC DEPTH (g/cm^2)
TIME (hr)



PARTICLES / M²-STER-SEC
140
120
100
80
60
40
20
15-160 MEV
ELECTRONS
160-320 MEV
ELECTRONS
12
16
20
24 hr
LT



6000
5000
100
80
60
40
20
PARTICLES / M^2-STER-SEC
ALL
EVENTS
5-15 MEV
ELECTRONS
12
16
20
24
hr
LT


TOTAL
ELECTRONS
①
②
②
③
④
②
10
1
0.1
10
100
1000
ELECTRONS / M^2-STER-SEC-MeV
ELECTRON ENERGY (MeV)

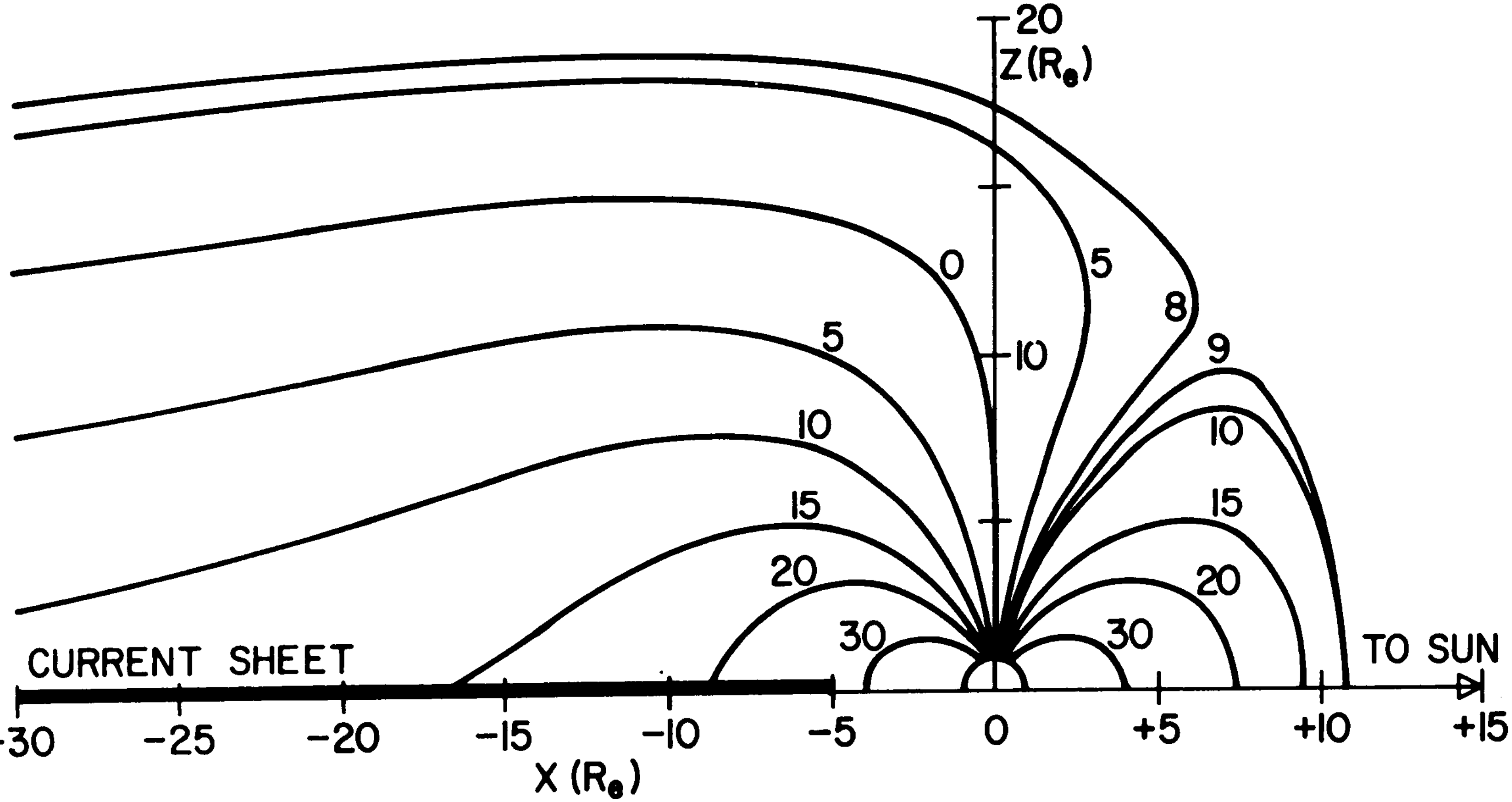
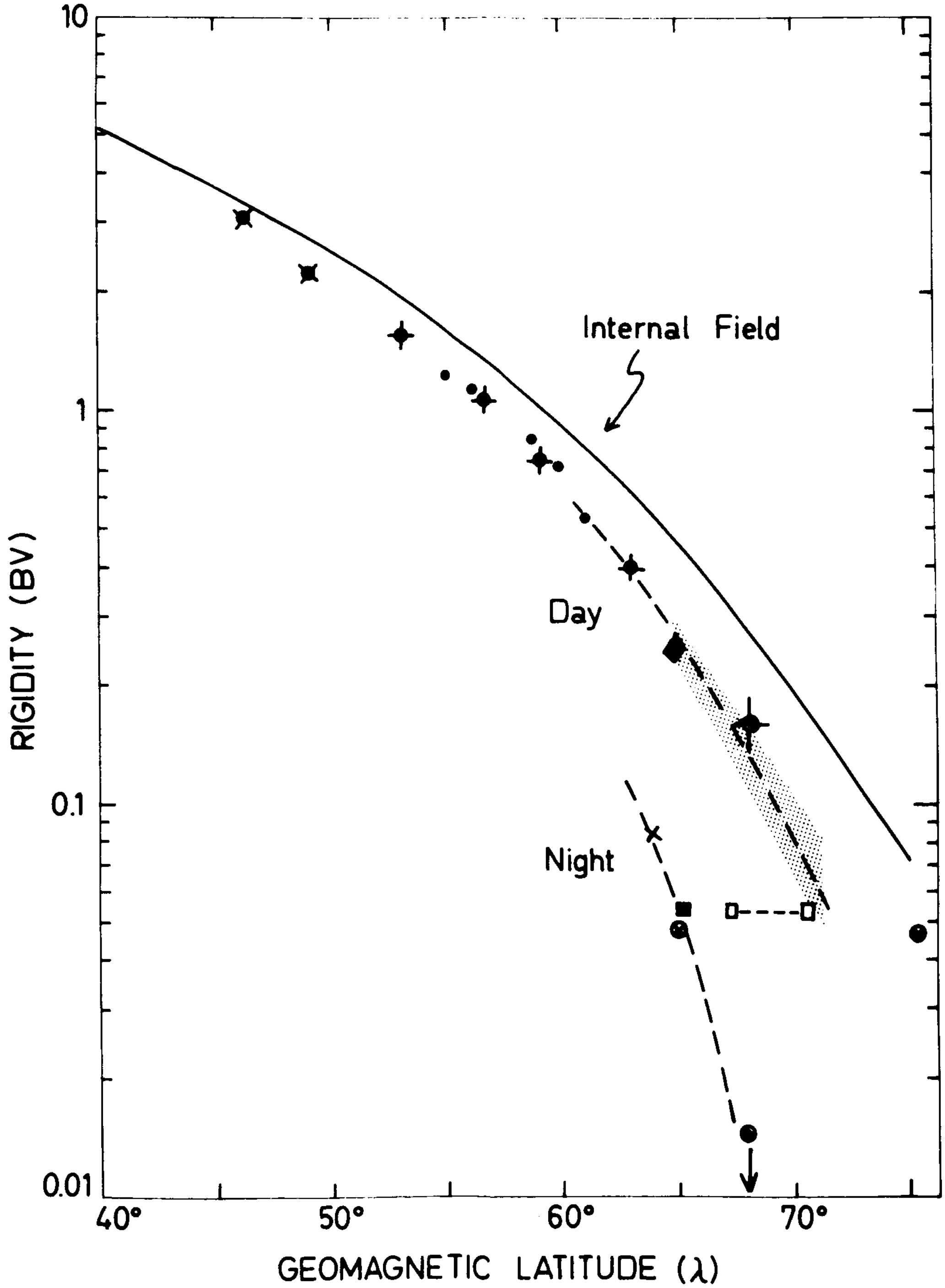
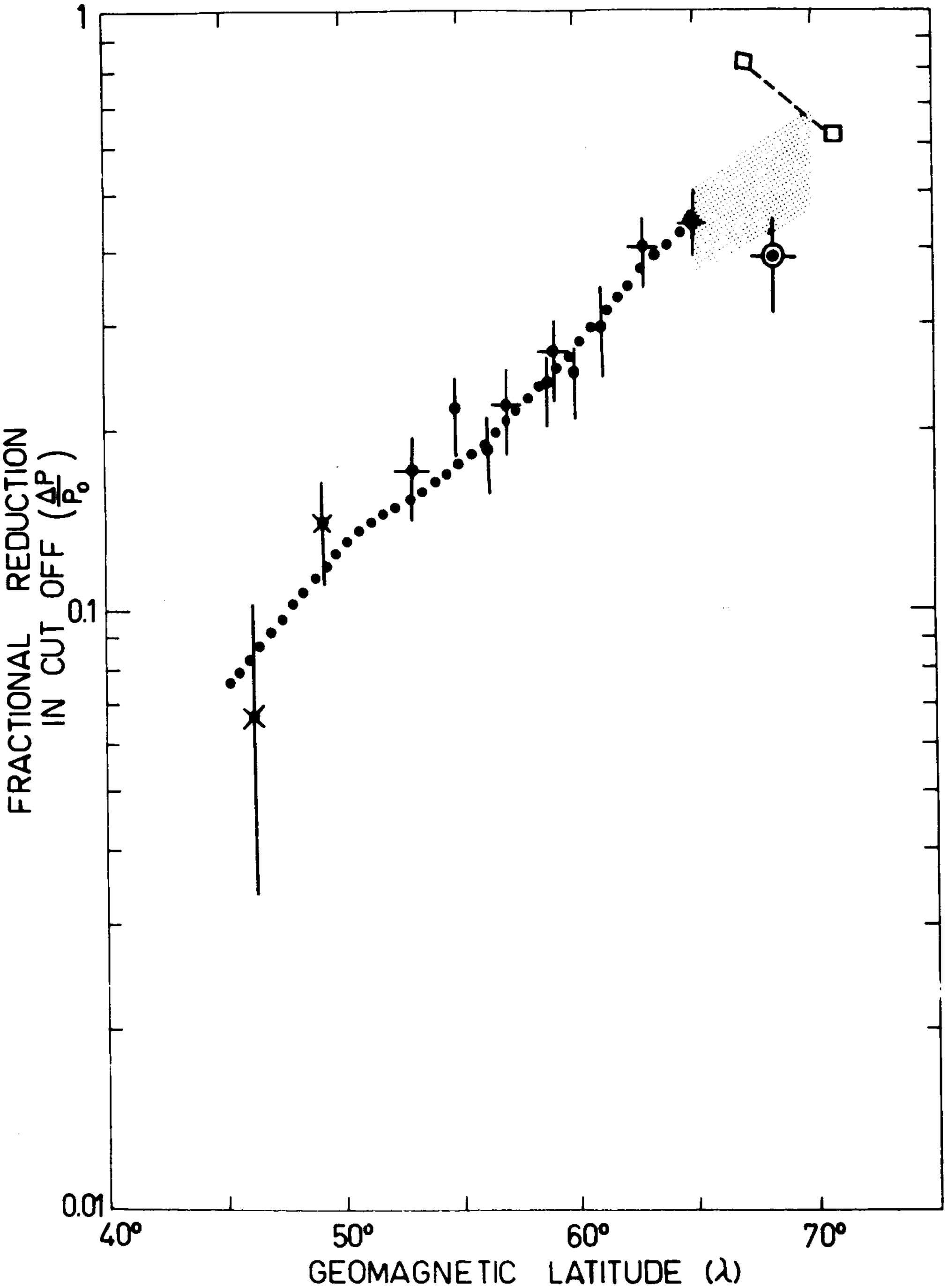
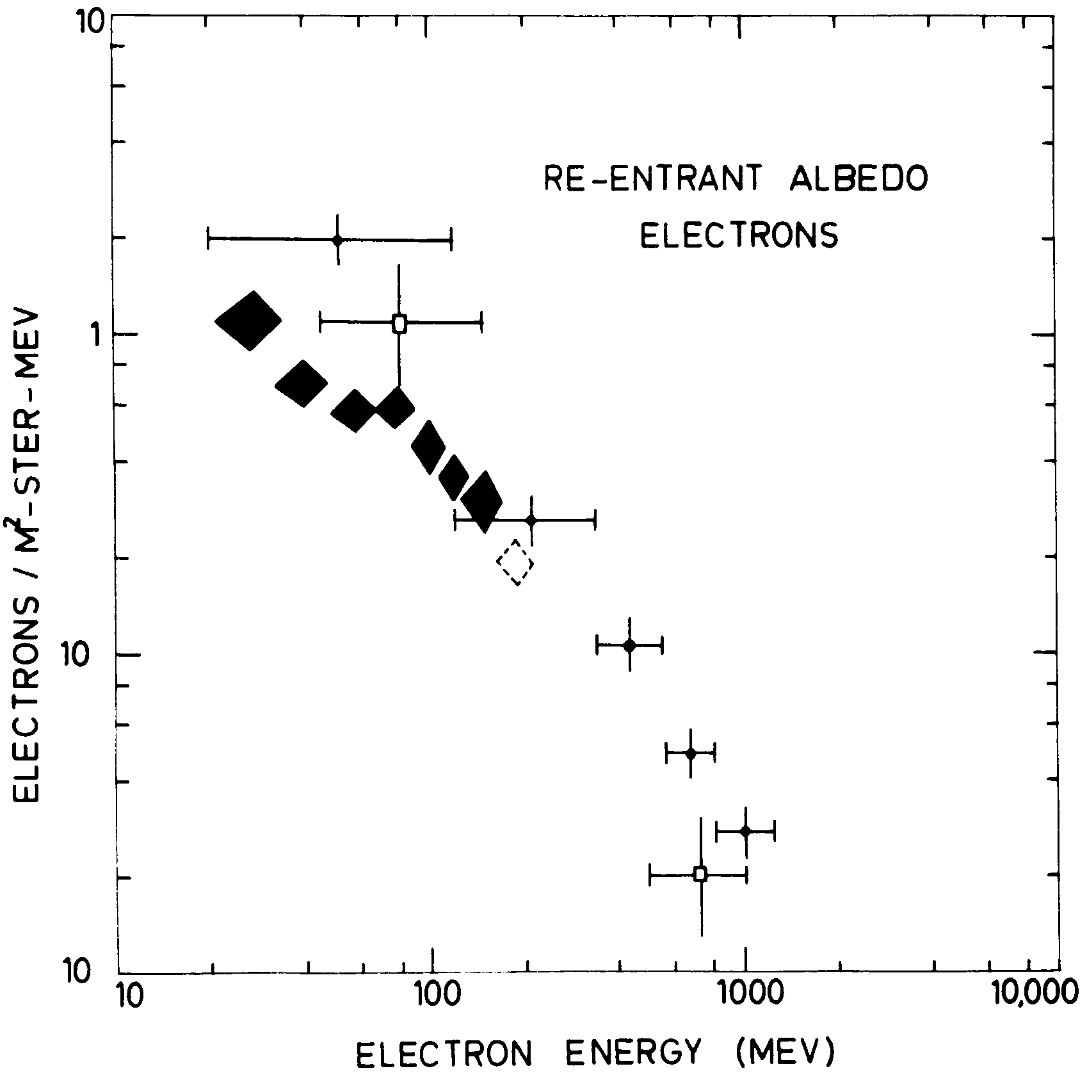

20
Z(Re)
10
0
5
8
9
5
10
10
15
15
20
20
30
30
TO SUN
CURRENT SHEET
-30
-25
-20
-15
-10
-5
0
+5
+10
+15
X (Re)

FIGURE 5

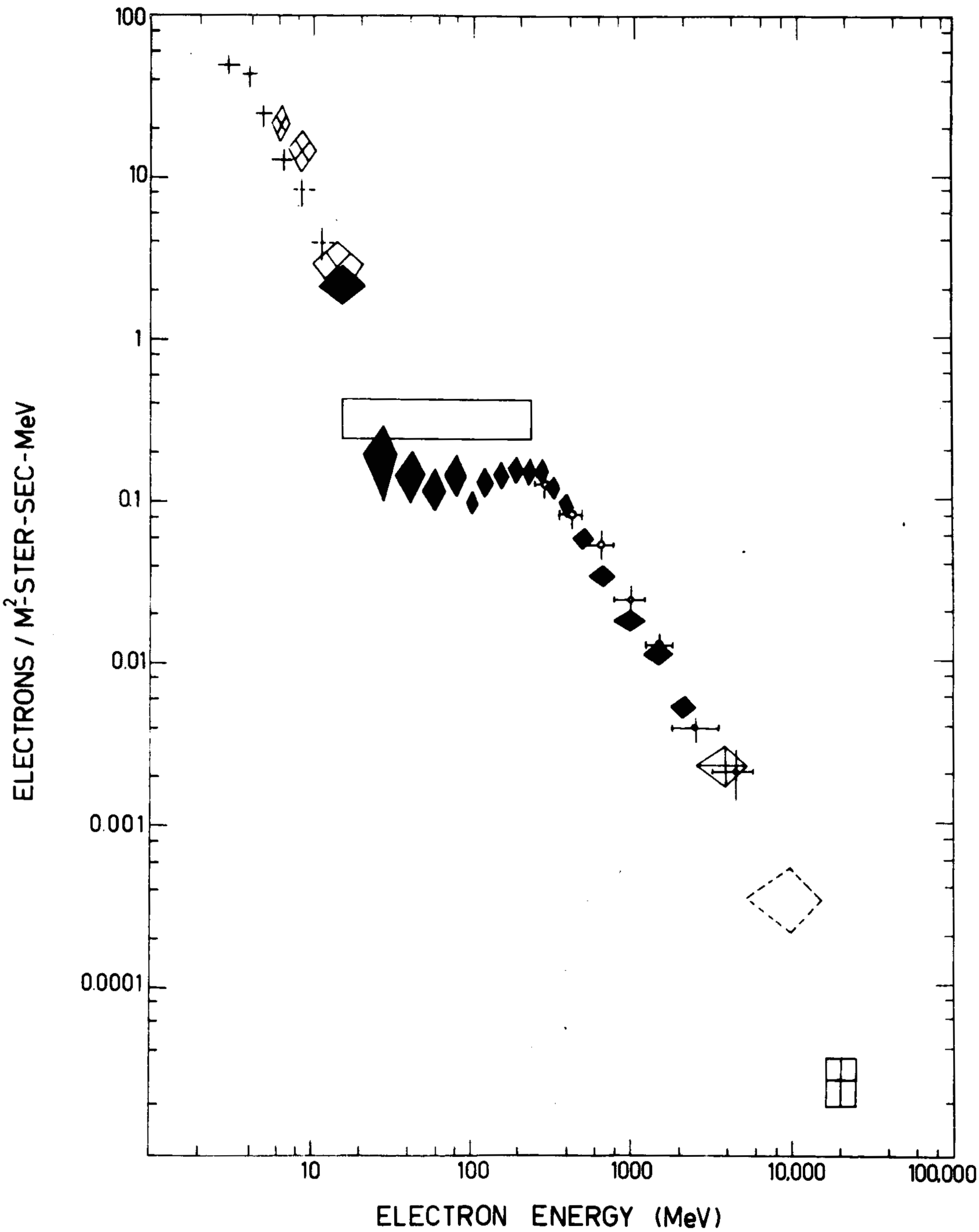

10
1
0.1
0.01
RIGIDITY (BV)
Internal Field
Day
Night
40°
50°
60°
70°
GEOMAGNETIC LATITUDE (λ)



1
0.1
0.01
40°
50°
60°
70°
GEOMAGNETIC LATITUDE (λ)
FRACTIONAL REDUCTION IN CUT OFF $(\frac{\Delta P}{P_o})$



RE-ENTRANT ALBEDO
ELECTRONS
ELECTRONS / M²-STER-MEV
ELECTRON ENERGY (MEV)
10
1
10
10
10
100
1000
10,000


100
10
1
0.1
0.01
0.001
0.0001
ELECTRONS / M^2-STER-SEC-MeV
10
100
1000
10,000
100,000
ELECTRON ENERGY (MeV)